

FACILITY ACTIVATION AND CHARACTERIZATION FOR IPD OXIDIZER TURBOPUMP

COLD-FLOW TESTING AT NASA STENNIS SPACE CENTER

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ABSTRACT

The Integrated Powerhead Demonstrator (IPD) is a 250K lbf (1.1 MN) thrust cryogenic hydrogen/oxygen engine technology demonstrator that utilizes a full flow staged combustion engine cycle. The Integrated Powerhead Demonstrator (IPD) is part of NASA's Next Generation Launch Technology (NGLT) program, which seeks to provide safe, dependable, cost-cutting technologies for future space launch systems. The project also is part of the Department of Defense's Integrated High Payoff Rocket Propulsion Technology (IHPRT) program, which seeks to increase the performance and capability of today's state-of-the-art rocket propulsion systems while decreasing costs associated with military and commercial access to space. The primary industry participants include Boeing-Rocketdyne and GenCorp Aerojet. The intended full flow engine cycle is a key component in achieving all of the aforementioned goals.

The IPD Program achieved a major milestone with the successful completion of the IPD Oxidizer Turbopump (OTP) cold-flow test project at the NASA John C. Stennis Space Center (SSC) E-1 test facility in November 2001. A total of 11 IPD OTP cold-flow tests were completed. Following an overview of the NASA SSC E-1 test facility, this paper addresses the facility aspects pertaining to the activation and the cold-flow testing of the IPD OTP. In addition, some of the facility challenges encountered during the test project are addressed.

INTRODUCTION

The Integrated Powerhead Demonstrator (IPD) is a 250K lbf (1.1 MN) thrust cryogenic hydrogen/oxygen engine technology demonstrator that utilizes a full flow staged combustion engine cycle. The Integrated Powerhead Demonstrator (IPD) is part of NASA's Next Generation Launch Technology (NGLT) program, which seeks to provide safe, dependable, cost-cutting technologies for future space launch systems. The project also is part of the Department of Defense's Integrated High Payoff Rocket Propulsion Technology (IHPRT) program, which seeks to increase the performance and capability of today's state-of-the-art rocket propulsion systems while decreasing costs associated with military and commercial access to space. The primary industry participants include Boeing-Rocketdyne and GenCorp Aerojet. The intended full flow engine cycle is a key technology in achieving all of the aforementioned goals.

IPD is the first engine development program to examine the full flow staged combustion cycle¹ which utilizes oxygen rich preburner exhaust gases to drive an oxygen rich turbopump. IPD is also the first engine to utilize hydrostatic bearings in both turbopumps. The full flow cycle greatly lowers turbine temperatures due to the complete utilization of the oxygen flow to drive the oxygen turbine. The IPD engine will demonstrate significant engine life and maintenance improvements over the current space shuttle main engine.

Component testing in support of the future IPD integrated engine system testing was pursued at the NASA John C. Stennis Space Center (SSC) E-1 component test facility and at a GenCorp Aerojet test facility. With regards to the NASA SSC E-1 test facility, a series of

turbopump test projects were initiated in 1999. The first IPD test effort to be completed at the E-1 test facility was the cold-flow testing of the IPD Oxidizer Turbopump (OTP) that concluded in late 2001. The cold-flow testing (11 total tests) involved feeding the pump liquid nitrogen and the associated turbine gaseous nitrogen to assess pump performance.

Hot-fire testing of the IPD OTP was vigorously pursued after the successful completion of the IPD OTP cold-flow test series. More specifically, hot combustion gases from an oxygen-rich preburner fed the turbine side of the IPD OTP while liquid oxygen fed the pump side of the IPD OTP.² A series of nine tests were completed in October 2002 to characterize the oxygen-rich preburner. Subsequently, the oxygen-rich preburner was mated to the IPD OTP and the combined system was successfully tested 12 times with testing ending in June 2003.²

Following an overview of the NASA SSC E-1 test facility, this paper addresses the facility aspects pertaining to the activation and the cold-flow testing of the IPD OTP. In addition, some of the facility challenges encountered during the test project are addressed.

E-1 TEST FACILITY

The NASA John C. Stennis Space Center (SSC) is located in Hancock County, MS and one aspect of its mission is the management and operation of a comprehensive and unique set of test facilities and test capabilities. A wide range of rocket propulsion test work occurs at SSC including full-scale engine test activities at test facilities A-1, A-2, B-1 and B-2 as well as combustion device research and development activities at the E-Complex (E-1, E-2, E-3 and E-4) test facilities.³⁻¹³

The largest facility at E-Complex is E-1, a depiction of which is shown in Figure 1. E-1 is comprised of three distinct test cells (Cells 1, 2 and 3) and is particularly suited for cryogenic engine component testing. Typical engine components that can be tested at E-1 include turbopump assemblies, combustion devices (e.g., preburners) and thrust chamber assemblies. The attractive feature of E-1 is the ability to deliver high flow rates of propellants at high pressures.

Components having thrust levels up to 750K lbf (3.3 MN) can be tested at E-1. Specific commodities available at E-1 include liquid oxygen (LOX), liquid hydrogen (LH2), gaseous hydrogen (GH2), liquid nitrogen (LN2), gaseous nitrogen (GN2) and gaseous helium (GHe). Cryogenic fluids can be supplied to the test cells at pressures exceeding 8000 psi (55 MPa).

The electrical capabilities associated with E-1 include a control system, various instrumentation systems, low-speed data acquisition system (LSDAS), high-speed data acquisition system (HSDAS), data processing capability, video system (low and high speed) and various power utilities. Ancillary facility systems include a plume impingement area, hydraulic system and a communications system. In addition, each test cell is equipped with a deluge water system.

With regards to future work, efforts are currently either underway or planned to upgrade and enhance testing capabilities at E-1. The most significant upgrade currently underway is the



Figure 1. E-1 Test Facility comprised of Cells 1, 2 and 3.

addition of high-pressure hydrocarbon capability at E-1, potentially to 1Mlbf (4.4 MN) thrust, thereby enabling LOX/RP testing. A major upgrade of the gas pressurization systems is also underway. Other supporting enhancements are planned for the data acquisition and control systems (DACS).

TEST ACTIVITY DISCUSSION

The first IPD test effort initiated at the E-1 test facility was the cold-flow testing of the IPD Oxidizer Turbopump (OTP). The objective of the cold-flow test series (11 total tests) was to assess the IPD OTP performance. Generally, the first tests conducted were at the lower power levels, and with each successful test, the power level was gradually increased. In the sections that follow, aspects of the facility activation, including design and operational challenges, associated with the testing of the IPD OTP are outlined.

A variety of facility activities from planning to design to fabrication/installation are part of the process of preparing for the testing of a particular test article. Upon project initiation, project management activities such as requirements definition and schedule development are undertaken. As requirements and project planning progress, design (e.g., structural, mechanical, electrical) activities are initiated. Facility and Special Test Equipment (STE) designs are developed that allow the facility to meet the various test article interface requirements that have been previously established. Note that the STE is the hardware (e.g., piping) that connects the test facility to the test article hardware. Following the appropriate design reviews, the designed systems are fabricated and installed. The installed facility and STE systems are subsequently tested (i.e. activated) to verify that the systems meet all of the agreed upon requirements. Once the facility and the test article have been properly integrated and a successful Test Readiness Review (TRR) completed, the testing phase begins.

Facility activation involves testing the various facility systems to ensure that the facility can meet the test article requirements, for example, propellant flow rate, interface pressure(s) and interface temperature(s). Facility activation for the IPD OTP test series primarily involved assessing the facility systems that fed propellant to the IPD OTP turbine and pump systems. More specifically, high-pressure, ambient-temperature gaseous nitrogen was delivered to the IPD OTP turbine and low-pressure liquid nitrogen was delivered to the pump side of the IPD OTP.

TURBINE DRIVE SYSTEM ACTIVATION

The high-pressure GN2 was delivered to the test article through the high-pressure oxidant system at E-1. The high-pressure oxidant system was used to supply GN2 to the IPD OTP since that system would supply the medium at the required pressures. Succinctly, the system consisted of an ultra-high pressure pressurization system (GN2), a run tank pressure control valve (PCV), a vacuum-jacketed run tank that typically houses LOX and various facility and STE piping and components that supplied the GN2 to the IPD OTP. Since the aforementioned vacuum-jacketed run tank was previously used for LOX service and ambient temperature GN2 was a requirement, the run tank was warmed prior to initiating the IPD OTP tests. The large volume run tank was warmed from cryogenic temperatures by continuously passing heated GN2 through it at various pressure levels over the course of one week. From the vacuum-jacketed run tank, GN2 was supplied to the IPD OTP through a screen, a subsonic venturi and finally a turbine drive valve that was an 8" (203 mm) hydraulically operated variable position valve (VPV).

Several facility operational control philosophies were attempted with the goal of meeting the IPD OTP turbine side interface requirements. The desired pressure profile at the turbine interface was a steep pressurization at the test start followed by a constant pressure for the duration of the test. All of the control philosophies included operating the oxidant run tank in closed loop pressure control using the run tank pressure control valve (PCV). The first control philosophy was to use the turbine drive valve in a second pressure control loop, controlling turbine interface pressure during test start and steady state operation. Under this control philosophy, numerous attempts were ultimately unsuccessful in defining a single set of gain

parameters for the turbine drive valve pressure control loop that would simultaneously meet the startup pressurization rate requirements and the pressure stability requirements. The task of directly controlling interface pressure was complicated by the small volume between the turbine drive valve and the test article turbine interface and a possible inversion in the flow coefficient curve of the turbine drive valve.

The remaining control philosophies involved operating the turbine drive valve in open loop (position control) with the valve ramp rate determining the turbine interface pressurization rate during test start. Since the turbine drive valve was to be fully opened during all tests, different run tank pressure settings were required for each power level. During the activation tests, the run tank pressure slumped at test start below the pre-flow set pressure. The second control philosophy used a high integral gain setting to bring the run tank pressure under flowing conditions back up to the pre-flow set pressure. This philosophy too was abandoned when determining a single set of gain parameters that would meet test requirements proved elusive. No gain settings for any activation test met the required short pressure recovery time and simultaneously met the pressure stability requirements.

Finally, a “droop” controller philosophy was adopted. This philosophy is the same as the previous one without the control pressure returning to the pre-flow set pressure. This was termed a droop controller because the run tank pressure slump at test start remains for the duration of the test. The controller exhibited this characteristic because it relied primarily on proportional gain and minimal integral gain.

The turbine drive valve ramp rate determined the turbine inlet pressurization rate. When the turbine drive valve achieved the full open position, all system pressures remained constant for the duration of the test. An example of the characteristics of the turbine drive system for a select power level is shown in Figure 2. The advantage of the droop controller was that the turbine inlet pressurization rate and the pressure stability requirements were easily achieved for each power level. The major disadvantage of the droop controller was that the desired run tank pressure during the test was not the same as the pressure set point in the controller, which complicated test planning and record keeping.

Turbine Inlet Pressure Control Characteristics

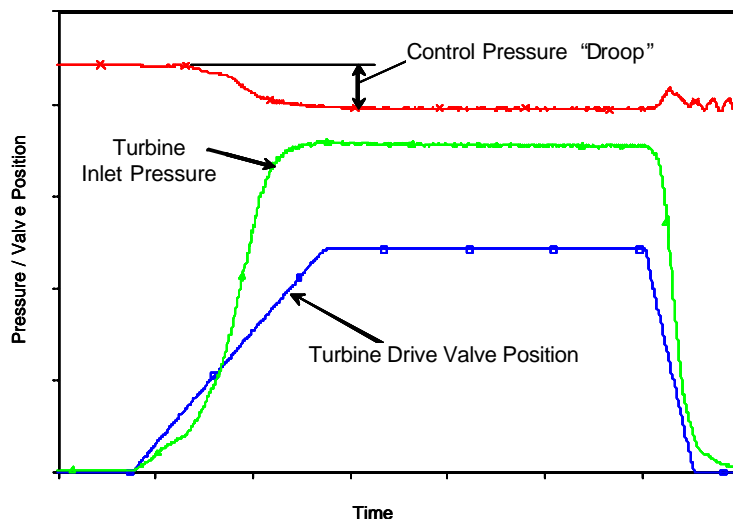


Figure 2. The run tank pressure, interface pressure and turbine drive valve position plotted as a function of time for a select power level activation test.

In addition to defining the control philosophy and demonstrating acceptable pressure control, other pertinent characteristics of the turbine drive system were catalogued. The GN2 temperature profile and the maximum run duration were determined through activation tests. Several discharge orifices were employed during activation including a turbine simulator orifice, a turbine backpressure orifice and a turbine discharge orifice. The discharge coefficients for all of these orifices were determined through activation tests via comparison to the flow rate calculated using the calibrated venturi.

PUMP DRIVE SYSTEM ACTIVATION

The IPD OTP cold-flow test series was performed using LN2 as the pump fluid supplied from a low-pressure run tank. Since the objectives of the test series did not specifically require

LOX, LN2 was used as the operating fluid since its properties are similar to those of LOX and the risk of an oxygen-based fire is eliminated. The facility system associated with the pump drive system of the IPD OTP consisted of a high-pressure GN2 pressurization system, a regulator, a run tank PCV, a vacuum-jacketed run tank (low-pressure), a run tank isolation valve, a pump inlet valve, a screen, a pump discharge valve and a pump discharge orifice. Flow measurements were acquired using a non-cavitating venturi in the pump discharge system. The flow rate was not measured in the pump inlet system.

The control scheme for the pump inlet system used the run tank in closed loop pressure control on the run tank bottom pressure. Using the tank bottom pressure as the process variable allowed the measurement to be near the PCV to avoid control latency problems while at the same time eliminating tank liquid level as a concern in set point selection. Since the elevation change from the tank bottom to the test article inlet is fixed, the head pressure between those locations is also a constant when the run line is filled with a column of liquid. Therefore, if the run tank pressure is maintained constant, the pump inlet pressure is a function of flow rate only and the associated run line pressure losses.

The primary performance objectives of the activation effort included procuring the necessary control parameters that minimized slump while maintaining a stable interface pressure, procuring the system resistances, procuring the LN2 temperature profile, procuring the pump discharge valve flow coefficient and the pump discharge orifice discharge coefficient.

Activation tests were performed on the pump inlet and pump discharge systems. The initial activation tests involved evaluating the stability of the run tank pressure as a function of the run tank PCV gain settings. These tests were performed with the tank isolation valve closed with no liquid flow from the run tank. After pressurizing the run tank, the run tank vent(s) were opened to simulate a demand on the pressurization system. The gain settings were evaluated based upon how well the pressure slump was minimized and steady state pressure was maintained. These tests were repeated at multiple run tank liquid levels and high-pressure GN2 supply pressures.

Subsequent to procuring an initial set of run tank PCV gain settings, activation cold flows were performed both with and without the pump discharge orifice installed. With the discharge orifice installed, the objectives of the activation tests included the measurement of the discharge coefficient of the orifice and to evaluate valve performance. The flow rate for this series of tests was below the full system flow rate due to the high resistance of the discharge orifice combined with the limited supply pressure of the low pressure pump feed system. Without the pump discharge orifice installed, the objectives of the activation tests included evaluating the pressure drop and general flow characteristics from the run tank through the pump inlet system at mass flow rates comparable to actual test flow rates. For example, the pressure loss of the pump inlet system as a function of mass flow rate is shown in Figure 3 for a typical activation test. The flow data is represented by the diamond symbols and the line represents the best-fit curve to that data. The data represented in Figure 3 was used to determine a run tank set pressure for a required mass flow rate and a pump inlet pressure. The scatter in the pressure loss data shown in Figure 3 was primarily due to the manner in which each flow set point was achieved. More specifically, the pump discharge valve was "stair-cased" to meet each flow set point. The practice of "stair-casing" valve movements to different set points during valve characterization tests is no

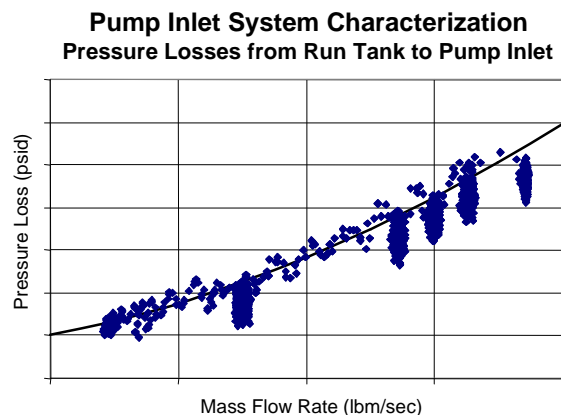


Figure 3. The pressure loss plotted as a function of mass flow rate for the pump inlet system. The symbols represent the data and the line represents the best-fit curve.

longer pursued. Currently, valve commands are programmed to ramp in a smooth and continuous fashion significantly reducing test data scatter.

During activation of the low-pressure oxidant system in preparation for IPD OTP cold flow testing, it became apparent that the thermocouples in the system were not yielding accurate temperatures. The first problem found was that the thermocouples were not electrically grounded properly, which shifted the temperature measurement. In addition, while performing LN2 dip tests, it was found that the thermocouple readings did not match the standard thermocouple tables at cryogenic temperatures. The thermocouple measurement accuracy problems were solved after correcting the grounding problems and generating new individual probe-specific thermocouple tables using an LN2 calibration point.

During IPD OTP cold-flow testing, problems with the pressure regulator upstream of the run tank PCV developed primarily due to rapid flow transients. A variety of remedies were employed to address the undesirable behavior of the pressure regulator including adjusting the regulator set pressure and using different components. The remedies allowed for the completion of the test series.

SUMMARY AND CONCLUSIONS

Completion of the IPD OTP cold-flow test series achieved a major milestone for both NASA SSC and the IPD Program. The test series allowed for the various systems associated with the facility to be exercised and as a result, a number of significant facility improvements were achieved.

Typically when facility issues develop, the solution can involve a trial-and-error methodology that is often costly and time consuming. Considerable strides have recently been made in developing an in-house thermodynamic fluid model that is used to simulate facility systems. Both transient and steady state predictions of process variables, such as pressure, can be made for a variety of test conditions. In addition, the model is able to accommodate control system inputs that result in a realistic simulation of the facility systems. It is anticipated with further model use and enhancements, the extent of activation testing and problem resolution testing will be minimized, thus achieving cost and schedule savings.

FUTURE WORK

Subsequent to the completion of the IPD OTP cold-flow testing efforts, the IPD OTP was successfully tested under hot-fire conditions (i.e., a preburner feeding the turbine side of the OTP) at E-1 Cell 3 between March 2003 and June 2003.² In addition, the IPD fuel turbopump (FTP) was successfully tested under cold-flow conditions at E-1 Cell 2 between August 2003 and October 2003. Successful completion of both IPD OTP and IPD FTP concluded IPD component testing at the NASA SSC E-1 test facility. Future work at NASA SSC with regards to the IPD Program is focused upon IPD Integrated Engine System Testing that is scheduled to begin in late 2004. More specifically, the complete 250K lbf (1.1 MN) thrust IPD engine system shall be tested at E-1 Cell 3.

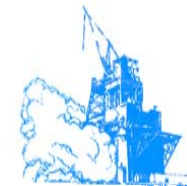
From a facility perspective, upgrades to the E-1 test facility are frequently pursued to continue to refine this premier component test facility. The most significant upgrade currently underway at the E-1 test facility is the addition of high-pressure hydrocarbon run tanks allowing for the testing of LOX/RP-based rocket components. Increased testing durations will also be possible following ongoing upgrades of the ultra-high pressure gas delivery system.

ACKNOWLEDGMENTS

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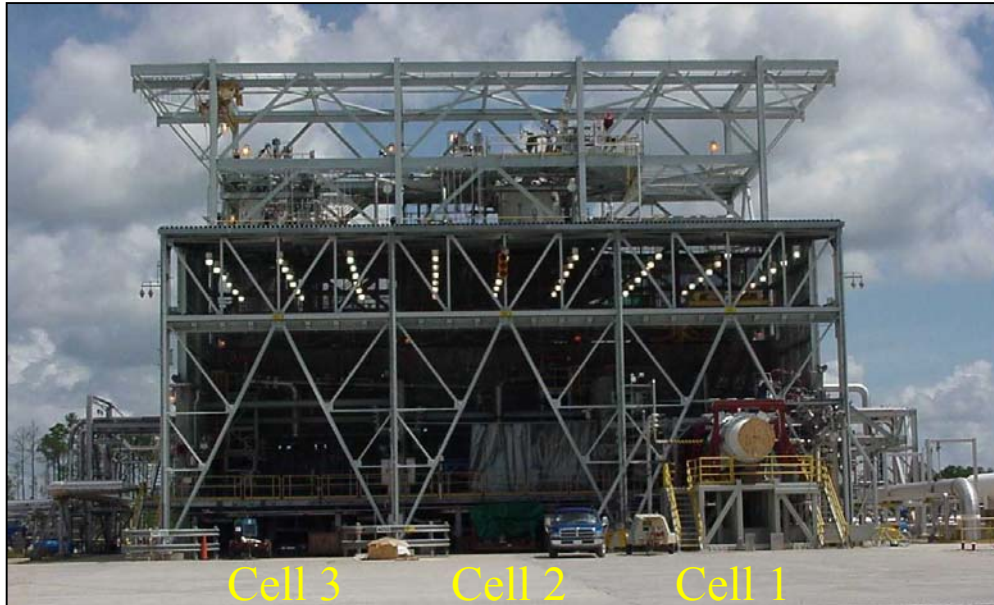
Facility Activation and Characterization for IPD Oxidizer Turbopump Cold-Flow Testing at NASA Stennis Space Center

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E-1 Test Stand Capability



High Pressure Capabilities

- $\text{LO}_2/\text{LH}_2 \sim 8,500 \text{ psi}$
- $\text{RP} \sim 8,500 \text{ psi}$
- $\text{GN/GH} \sim 15,000 \text{ psi}$
- $\text{GHe} \sim 10,000 \text{ psi}$
- Long run durations

State of the Art Data Acquisition and Control systems

- E1 Cell 1
 - Primarily Designed for Pressure-Fed $\text{LO}_2/\text{LH}_2/\text{RP}$ & Hybrid-Based Test Articles
 - Thrust Loads up to 750K lb_f (horiz.)
- E1 Cell 2
 - Designed for LH_2 Turbopump & Preburner Assembly Testing
 - Thrust Loads up to 60K lb_f
- E1 Cell 3
 - Designed for LO_2 Turbopump, Preburner Assembly & Engine System Testing
 - Thrust Loads up to 750K lb_f

Legend

RP: Kerosene blend for rockets

GN/GH: Gaseous Nitrogen and Hydrogen

GHe: Gaseous Helium



E-1 Testing History



TRW 650K Thrust Chamber Hot Fire Test (Cell 1)



250K Hybrid Motor Test Firing (Cell 1)



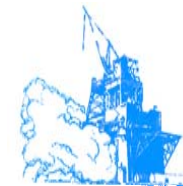
IPD Liquid Hydrogen Turbopump Test (Cell 2)



IPD Liquid Oxygen Turbopump Test (Cell 3)



IPD Program

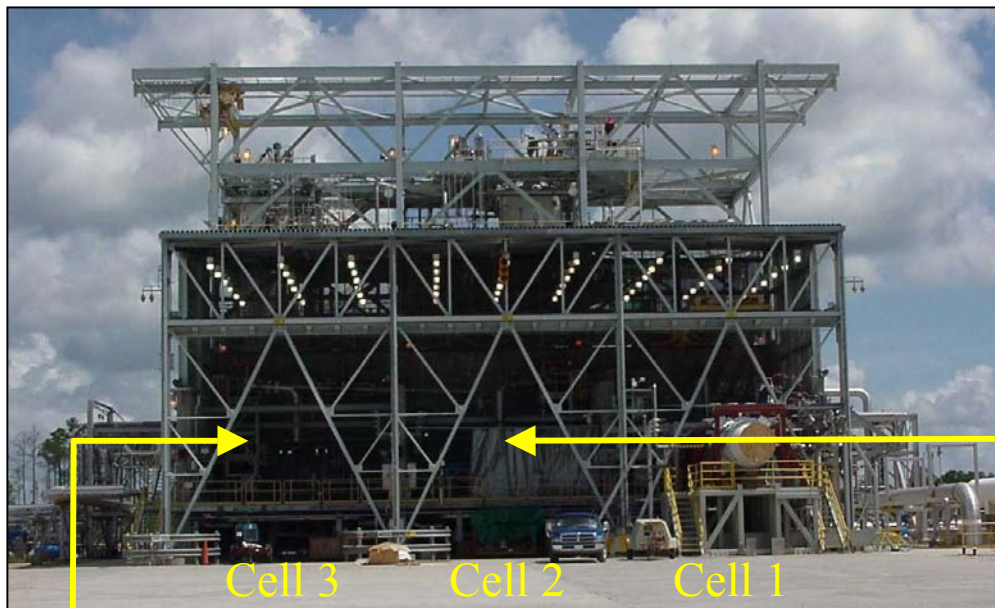
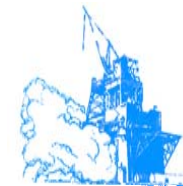


- Integrated Powerhead Demonstrator (IPD) Program
 - 250Klb_f Thrust Cryogenic Hydrogen/Oxygen Engine
 - Full Flow Staged Combustion (FFSC) Engine Cycle
 - Funding Through the NASA Next Generation Launch Technology (NGLT) Program
 - Funding Through the Department of Defense Integrated High Payoff Rocket Propulsion Technology (IHPRPT) Program
 - Team Effort
 - ✓ Aerojet
 - ✓ AFRL
 - ✓ Boeing
 - ✓ NASA MSFC
 - ✓ NASA SSC





IPD Testing at the E-1 Test Stand



1) IPD FTP Cold-Flow Testing (Complete)

Cell 3

Cell 2

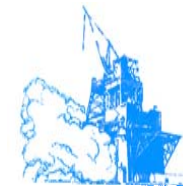
Cell 1

1) IPD OTP Cold-Flow Testing (Complete)

2) IPD Workhorse Preburner Testing (Complete)

3) IPD OTP Hot-Fire Testing (Complete)

4) IPD Engine System Testing (Begins Early 2005)



IPD OTP Cold-Flow Tests

Project Activities (Typical)

Project Formulation

Design

Procurement

Construction

Facility Activation

Testing

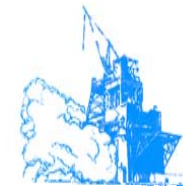
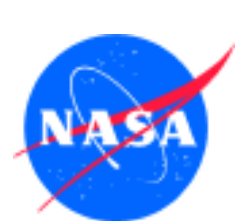
Demobilization

Propellant Interface Requirements:

- Low Pressure (LP) LN2
- High-Pressure (HP) GN2

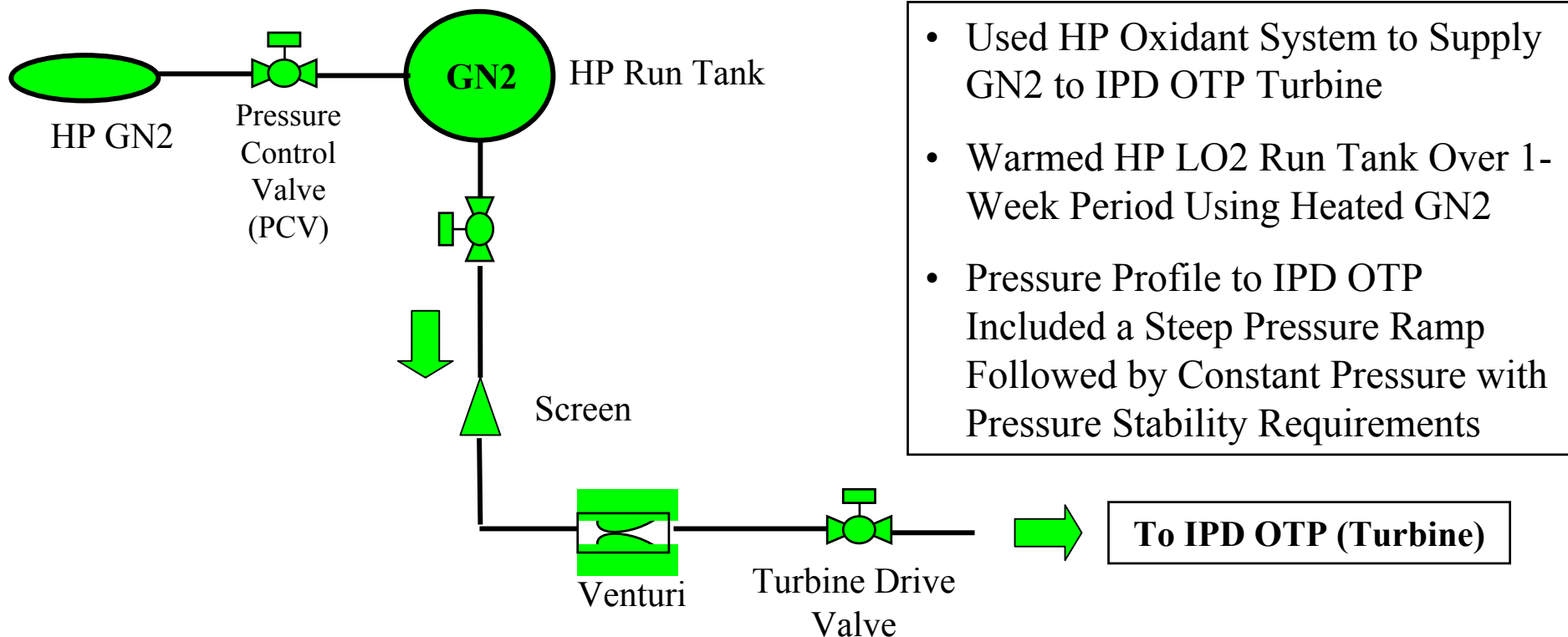
E-1 Cell 3 Facility Activation:

- Activate Facility System Feeding IPD OTP Turbine
- Activate Facility System Feeding IPD OTP Pump



IPD OTP Cold-Flow Tests

E-1 Cell 3 Schematic – High Pressure (HP) Oxidant System



Note: Not All Components Are Shown

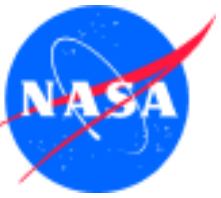


IPD OTP Cold-Flow Tests



HP Oxidant System Activation

- Used Ambient Temperature GN₂ as Medium Instead of Combustion Gases (Cold-Flow Test Series)
- Use Run Tank PCV in Closed Loop Control Achieve Target Run Tank Pressures
- Several Control Philosophies for the Turbine Drive Valve Attempted to Control Interface Pressure to IPD OTP
- Closed Loop Control of Turbine Drive Valve Did Not Meet Interface Pressure Requirements (e.g., Pressure Stability) Due to
 - Small Volume Between Turbine Drive Valve & IPD OTP
 - Unusual Flow Coefficient Curve of Turbine Drive Valve
- Open Loop Control (e.g., Position Control) Philosophies of Turbine Drive Valve Met with Greater Success



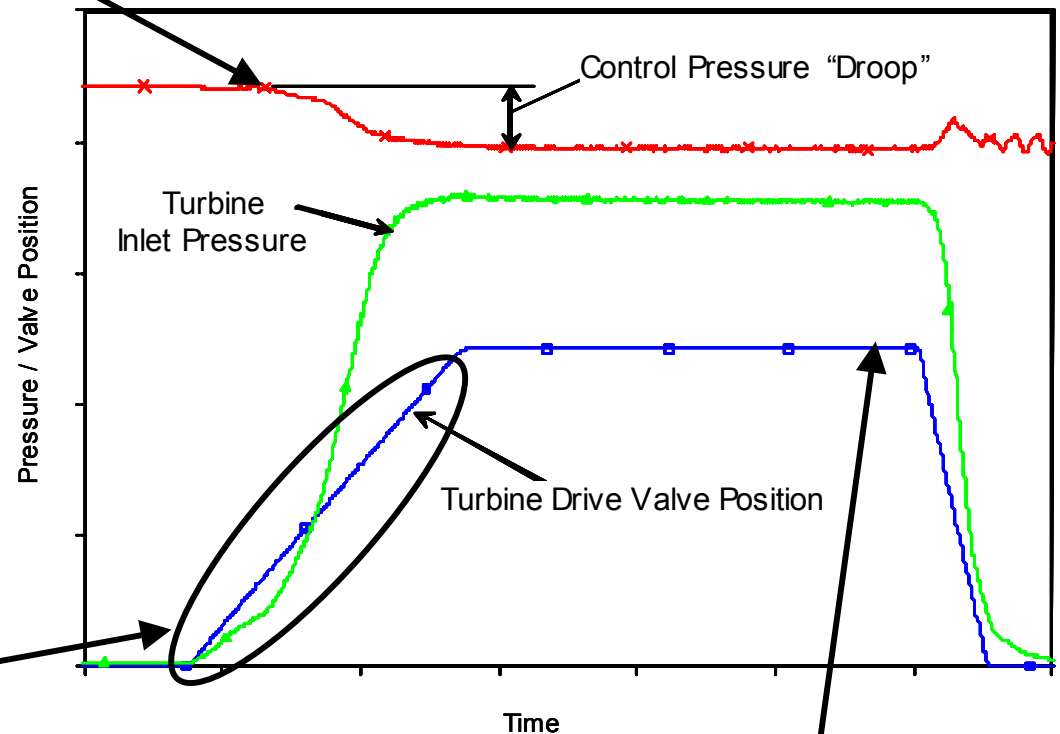
IPD OTP Cold-Flow Tests



HP Oxidant System Activation

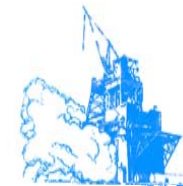
- Run Tank Pressure “Drooped” Below Set Point Under Flowing Conditions
- Aggressive PCV Integral Gain Settings Alleviated the “Droop” Issue, but Resulted in an Undesirable Non-Constant Pressure Profile
- To Achieve Interface Requirements, Allow for “Droop” & Maintain Constant Pressure
- Disadvantage of Philosophy Was Establishing the “Droop” for Each Different IPD OTP Test Condition

Turbine Inlet Pressure Control Characteristics



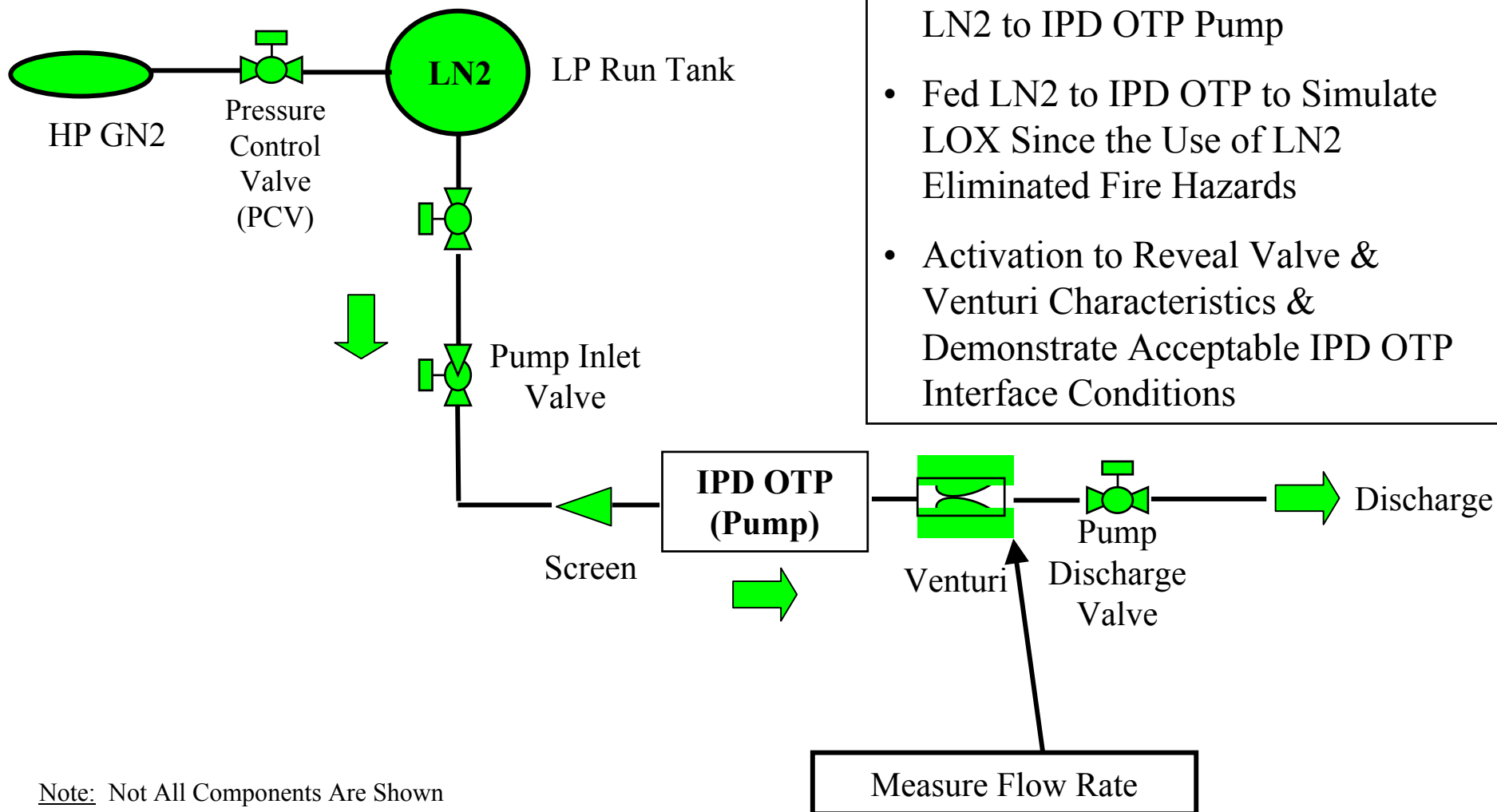
IPD OTP Interface Pressure Controlled by Turbine Drive Valve Ramp

Turbine Drive Valve Full Open



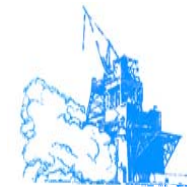
IPD OTP Cold-Flow Tests

E-1 Cell 3 Schematic – Low Pressure (LP) Oxidant System





IPD OTP Cold-Flow Tests

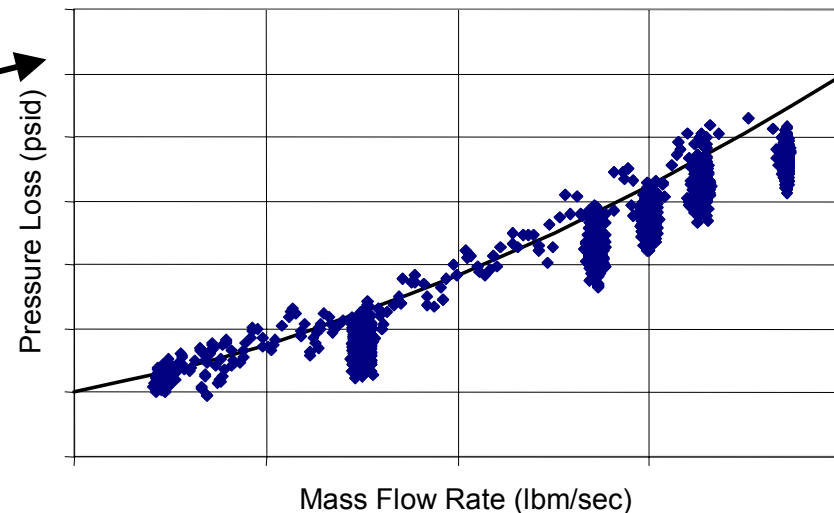


LP Oxidant System Activation

- Activation Tests Establish Facility Pipe System Resistance As A Function of Flow Rate
- Scatter in Data Due to Staircase Valve Commands – Improved Practice Now Allows for the Smooth Transition from One Valve Position to the Next



Pump Inlet System Characterization
Pressure Losses from Run Tank to Pump Inlet



IPD OTP Cold Flow Tests

- Team Effort – AFRL, Boeing, MSFC & SSC
- Completed 11 OTP Tests (Completed From May-01 to Nov-01)
- Cold-Flow Tests Performed from Blow-Down to High Power Levels





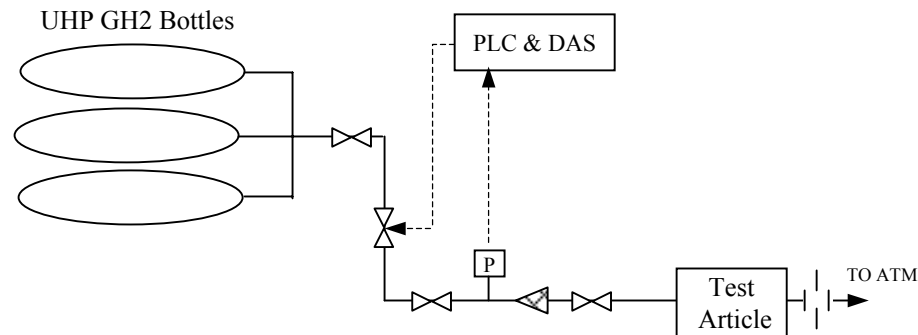
Analysis & Modeling Improvements



E-1 Cell 2 Modeling Effort

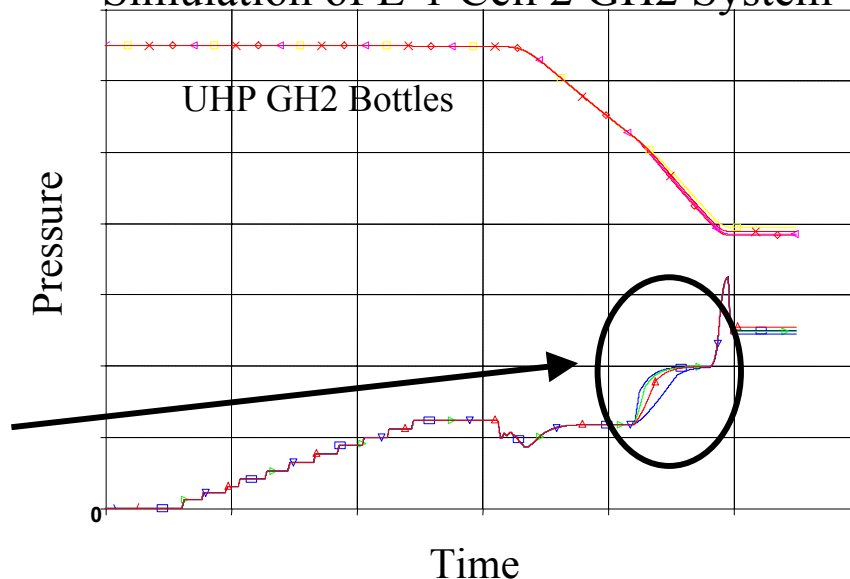
- Activation & Testing Cost, Schedule & Technical Performance Improving Due to Increased Analysis & Modeling Deployment
- Systems Thermodynamic Model Being Integrated into Design & Test Operations Activities
- Rocket Propellant Test Analysis (RPTA) Model Based Upon USUF, SSSF & Thermodynamic Process Constructs for Pressurization & Propellant Control Volumes

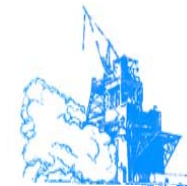
RPTA Model Simulates Effect of Different Valve Ramp Rates on System Pressure Near Test Article



RPTA Model Simulates Facility Systems

Simulation of E-1 Cell 2 GH2 System





Related & Future Work

IPD Related Work

- IPD Fuel Turbopump (FTP) Testing at E-1 Cell 2 Completed Aug-03 to Oct-03
- IPD Component Testing at SSC (E-1) Complete

IPD Future Work

- IPD Engine System Testing at E-1 Cell 3 Scheduled to Begin Early 2005



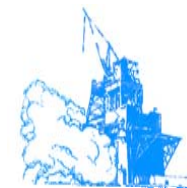
IPD FTP Test at E-1 Cell 2

E-1 Facility Future Work

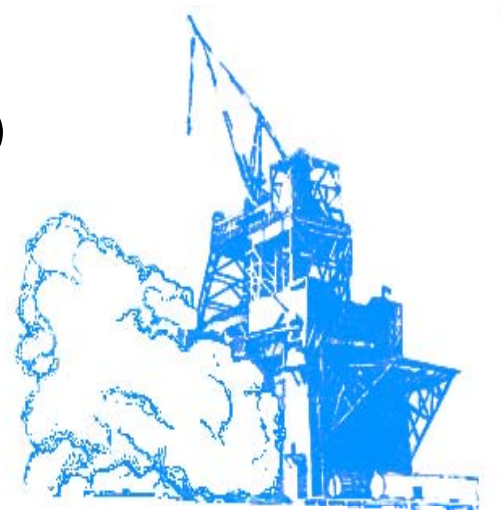
- Install High Pressure Hydrocarbon (RP) Propellant System
- Enhance Ultra High Pressure Gas Delivery System
- Upgrade Data Acquisition Systems (DACS)



Acknowledgements



- NASA
 - Propulsion Test Directorate (PTD)
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- Lockheed Martin Stennis Operations (LMSO)



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